

MILLIMETER-WAVE PROPERTIES OF THE ATMOSPHERE LABORATORY STUDIES AND PROPAGATION MODELING

Hans J. Liebe and Donald H. Layton*

Laboratory measurements have been performed at 138 GHz of water vapor attenuation α_x for pure vapor (H_2O) and its mixtures with air, nitrogen (N_2), oxygen (O_2), and Argon (Ar). Temperatures ranged from 8 to 43 °C, relative humidities from 0 to 95% and total pressures reached 1.5 atm. A computer-controlled resonance spectrometer was employed. The results are interpreted in terms of underlying absorption mechanisms. Broadening efficiencies m of mixtures $H_2O + N_2$, O_2 , Ar agree among themselves with those measured within cores of the 22 and 183 GHz H_2O absorption lines. The m -factors are applied to predict what share α_l of the total α_x results from the complete pressure-broadened H_2O spectrum. A substantial amount of the self-broadening term proportional to the square of vapor pressure is left unaccounted. The negative temperature coefficient of the excess absorption is consistent with a dimer ($H_2O)_2$ model. An empirical formulation of the experimental findings is incorporated into the parametric propagation model MPM that utilizes a local (30x H_2O , 48x O_2) line base to address frequencies up to 1000 GHz. Details of MPM are given in two Appendices. Predictions of moist air attenuation and delay by means of the revised MPM program generally compare favorably with reported (10 - 430 GHz) data from both field and laboratory experiments.

Key Words: atmospheric attenuation and delay; laboratory studies of moist air attenuation; millimeter/submillimeter-wave spectral range; propagation program MPM; radio path data

1. INTRODUCTION

Extending the radio spectrum into the near-millimeter region (NMMW: 0.1-1 THz) is an active area for research. Possible applications lie in short-range communications, radar, radiometry, and radio astronomy. Atmospheric effects of transmission and emission are described by the complex refractivity N that provides a measure of the interactions between radiation and the atmospheric propagation medium. A reliable N -model allows calculation of frequency-dependent rates for delay (real part) and attenuation (imaginary part) based on measurable meteorological variables. Dry air and atmospheric water vapor are major millimeter-wave absorbers; so are suspended droplets (haze, fog, cloud) and precipitating water drops that emanate from the vapor

*The authors are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U. S. Department of Commerce, Boulder, CO 80303-3328.

phase. Laboratory research and analytical studies have been conducted with the primary purpose of understanding power attenuation α (dB/km) and group delay β (ps/km). Emphasis was placed on the fundamental concepts that support an N formulation.

Refractivity N for moist air can be obtained, in principle, by a line-by-line summation over all molecular absorption lines. In practice, various approximations are employed to reduce labor and computer time, since the number of contributing spectral lines by the dominant absorbers (water vapor and oxygen) and by various trace gases (e.g., O_3) exceeds 10,000. A practical propagation model, indexed MPM (and described in Appendix A and B), consists of local H_2O (30x) and O_2 (48x) lines below 1 THz and an approximation to the contributions by H_2O lines above 1 THz [1] - [3].

The experiments have been performed at 138 GHz to measure absolute attenuation rates by dry air, moist air, water vapor, and water-vapor mixtures with nitrogen (N_2), oxygen (O_2), and argon (Ar) at temperatures between 8 and 43°C, total pressures up to 1.5 atm, and relative humidities between 0 and 95 percent. The experimentally observed absorption is not described by standard line shape models. Such failure reveals difficulties in modeling frequency, temperature, and pressure dependences for moist air attenuation. An unexplained excess is identified for which the name "water-vapor continuum" was coined since it appears to increase smoothly with frequency within the NMMW range.

Experimental studies are compared with model calculations. The MPM program is a user-friendly, PC-operated code that generates numerical values of $\alpha(f)$ and $\beta(f)$ for frequencies f up to 1000 GHz. Input parameters are five measurable atmospheric quantities: barometric pressure P , ambient temperature T , relative humidity RH (absolute humidity v), suspended droplet water content w , and rainfall rate R . Controlled laboratory measurements were limited to moist air studies (P , T , RH), and the data obtained at 138 GHz are reasonably complete and accurate to assess water vapor pressure and temperature dependences for the water-vapor continuum. Both variabilities point to the distinct possibility of an absorption mechanism related to water vapor that is not accounted for by molecular theory of H_2O .

This report is organized in three parts. The first part (Section 2) gives details of the experimental setup, its achieved performance, and a summary of reduced data. After many improvements, a detection sensitivity of

$\alpha_{\min} \approx 0.05 \text{ dB/km}$ or $1.2 \times 10^{-7} \text{ cm}^{-1}$ was realized. In the second part (Section 3), results from the laboratory experiments are applied (a) to calibrate the MPM program with an empirical continuum term, (b) to demonstrate the parametric flexibility of the code (i.e., f , $v(RH)$, and P can be selected as variables), and (c) to conjecture on the physical basis for a water vapor continuum that is defined by the limited H_2O line base of MPM. Finally Section 4 contains examples of recently reported data from laboratory and field experiments on water vapor absorption (10-430 GHz) and their comparison with MPM predictions.

2. LABORATORY STUDIES OF MOIST AIR ABSORPTION AT 138 GHZ

Controlled experiments that simulate atmospheric conditions provide test cases for studying specific contributions to N . Assessments of basic physical principles underlying the attenuation rate α are difficult to make from measurements in the actual atmosphere. The objective of this study was to measure water vapor (continuum) absorption. A test frequency of 138 GHz was selected because of its remoteness from local H_2O lines. The expected window attenuation falls in the range 0.1 to 5 dB/km and the required detection sensitivity calls for a long (>0.1 km) effective path length, which can be attained with a resonant absorption cell.

The response curve $A(f)$ of an isolated, high Q-value resonance is detected with a power (square-law) detector. Both, the peak value a_0 at center frequency f_R and the bandwidth b_0 spread over a range $f_R \pm b_0/2$ at the level $a_0/2$ might be used to detect the relative attenuation,

$$\alpha_r = 8.686(\sqrt{a_0/a} - 1) = 8.686(b/b_0 - 1) \quad \text{dB}, \quad (1)$$

of an absorbing gas that changes the corresponding quantities to a and b when introduced into the resonator. Around 138 GHz it is possible to design a compact (20 cm mirror spacing) Fabry-Perot resonator with a loaded Q-value on the order of 4×10^5 , which defines ($Q = f_R/b_0$) a resonance bandwidth, $b_0 = 350 \text{ kHz}$.

A crucial question to be resolved is whether amplitude (a_0/a) or frequency (b/b_0) detection schemes provide the optimum sensitivity for the spectrometer. After extensive testing it was found that digital averaging of $A(f)$, displayed over a frequency span $\Delta f_M = f_R \pm 6b_0$, was capable of resolving